A Technique to Measure Fine-dust Emission Potentials During Wind Erosion

David G. Chandler,* K. E. Saxton, J. Kjelgaard, and A. J. Busacca

ABSTRACT

Suspendable-size soil particles are released during wind erosion and transported downwind, impacting regional air quality. Of particular concern are those particles with a mean aerodynamic diameter of <10 µm (PM_{10}) and the finer subset of those <2.5 µm ($PM_{2.5}$). To estimate the air quality impact of wind erosion, the potential release from nondispersed soil of PM_{10} and $PM_{2.5}$ particles must be quantified for both those readily entrained existing particles and those generated by aggregate abrasion. A new laboratory technique was devised to determine the potential emission of these size particles by both processes from nondispersed soil samples. An emission cone in which the soil sample was suspended and rotationally abraded in an air stream was coupled with a standard measuring instrument for either PM_{10} or $PM_{2.5}$. Data of nondispersed soil samples compared with those dispersed showed significantly less emission potentials for the nondispersed. The $PM_{2.5}$ portion of the PM_{10} values ranged from 30 to 55% indicating significant air quality impacts by wind erosion in this region based on either standard. Results from Washington State showed spatial patterns closely related to soil morphology, and a linear relationship between dispersed and self-abrader PM_{10}, but not $PM_{2.5}$.

D ETERMINING RELEASE RATES of aerosol-size particulates from disturbed soils during wind erosion events is a critical step needed to incorporate air quality prediction into wind erosion models. Particulate aerosols arise from the soil surface when it is abraded by saltating aggregates and mineral grains and by direct entrainment from the soil surface because of turbulent eddies in surface winds (Kind, 1992; Loosmore and Hunt, 2000). Wind erosion prediction models generally consider the aerosols generated by these processes as a portion of the suspension component of the eroded soil (Mirzamostafa et al., 1998).

Particulate aerosols of primary concern to air quality are PM_{10} and $PM_{2.5}$. Ambient concentrations of PM_{10} and $PM_{2.5}$ have been selected as air quality indicators and are the bases of federal air quality regulation in the USA (USEPA, 1990b, 1997). During high wind events, large quantities of PM_{10} and $PM_{2.5}$ may be released from eroding source areas and transported long distances downwind as a fraction of the suspension component of the eroded soil (Stetler and Saxton, 1996).

The particle-size distribution of aerosols arising from wind erosion has been measured by several means (Gillette et al., 1974; Gillette and Walker, 1977; McTainsh et al., 1997) and modeled mathematically (Shao et al.,1993; Marticorena and Bergametti, 1995; Zobeck et al., 1999).

Potential aerosol release rates during wind erosion of soils have been quantified by such methods as sand-blasting aggregates in laboratory settings (Alfaro et al., 1998), measuring concentrations of fine particles during wind tunnel experiments (Mirzamostafa et al. 1998; Weinan et al., 1998) and by direct field measurements (Gillette et al., 1972, 1997; Nickling, 1978; Saxton et al., 2000).

Some have attempted to estimate the particulate emission potential by traditional dispersed soil analyses. However, since there is a fundamental difference between dispersed and nondispersed approaches to particle sizing (McCave and Syvitski, 1991), and soils do not undergo chemical dispersion during wind erosion events, these results are not directly applicable. Saxton et al. (2000) adapted a simple, single air-burst resuspension procedure to estimate the mass percentage of PM_{10} available for suspension from a soil (D). This resuspension method did not include particles released during aggregate abrasion, an important processes during wind erosion (Alfaro et al., 1998), and thus significantly underestimated the particulate emission potentials of the tested soils (Table 1).

A new laboratory method was developed to provide estimates of D for both PM_{10} and $PM_{2.5}$. The first objective was to develop a technique that did not require chemical dispersion and accounts for both preexisting particles and those released by aggregate abrasion. The results would need to discriminate among the wide variety of soils found across the study region of the Columbia Plateau. A second objective was to evaluate potential relationships between these nondispersed results with those of traditional dispersed-size fractions to provide a broader based estimating method utilizing existing soil data bases.

MATERIALS AND METHODS

A new laboratory measurement technique was designed, calibrated, and used for a wide variety of soils to determine PM_{10} and $PM_{2.5}$ emission potentials of nondispersed soil. This equipment consisted of a newly designed and constructed emitting cone coupled with a standard particulate monitoring instrument. The particles generated in the emitting cone were aspirated by the particulate monitor intake. The emission cone suspended both preexisting aerosol-size particles and abraded the aggregates as the soil sample tumbled and self-abraded, to provide additional particles.

The particulate measurement instrument was a Tapered Element Oscillating Microbalance (TEOM) 1400a Monitor (Rupprecht & Patashnick Co., Inc., Albany, NY). The TEOM is a Federal Reference Method (USEPA, 1990a) for monitoring PM_{10} and $PM_{2.5}$ in ambient conditions and commonly used

David G. Chandler, Dep. of Plants, Soils and Biometeorology, Utah State Univ., Logan, UT 84322; K.E. Saxton, USDA-ARS, L.J. Smith Hall-Washington State Univ., Pullman, WA 99164; J. Kjelgaard, Biological Systems Engineering Dep., Washington State Univ., Pullman, WA 99164; A.J. Busacca, Deps. of Crop and Soil Sciences and Geology, Washington State Univ., Pullman, WA 99164. Received 24 July 2001. *Corresponding author (dchandle@mendel.usu.edu).

Table 1. Average particle size <10 μm (PM$_{10}$) and particle size <2.5 μm (PM$_{2.5}$) emission potentials of several soils of the Columbia Plateau, as represented on the Washington state general soil map (Fig. 3, Boling et al., 1998) and selected Texas soils (TX), found by two methods of introducing the dust into a tapered element oscillating microbalance TEOM and expressed as percentages by mass of the soil sample tested. Average PM$_{10}$ and PM$_{2.5}$ content of those soils, as measured by laser diffraction following dispersion, and expressed as percentage by volume, are shown for comparison.

Soil	Self-abrader			Resuspension			Dispersed		
	Avg.	St. Dev.	n	Avg.	St. Dev.	n	Avg.	St. Dev.	n
	%			%			%		
					PM$_{10}$				
Dq	1.5	0.8	4	0.2	0.2	2	18.7	7.4	4
Ds	2.4	0.1	3	0.5	0.2	3	25.9	3.5	3
L1	2.1	0.7	8	0.6	0.1	4	24.6	5.7	8
L2	2.6	0.6	16	0.8	0.5	10	28.1	4.4	16
L3	3.1	0.8	4	0.6	0.3	4	28.4	3.8	4
L4	3.9	1.2	6	1.1	0.7	3	32.2	4.5	6
L5	4.1	0.1	3	0.7	0.1	3	37.8	5.0	3
TX	0.6	0.2	4				16.0	3.0	4
					PM$_{2.5}$				
Dq	0.5	0.3	4	0.2	0.1	2	8.0	2.2	4
Ds	1.3	0.4	3	0.4	0.2	2	11.7	1.5	3
L1	1.0	0.4	8	0.4	0.1	4	9.6	1.8	8
L2	1.4	0.5	16	0.3	0.1	10	11.9	1.6	16
L3	1.2	0.2	4	0.3	0.1	4	11.7	1.0	4
L4	1.9	0.8	6	0.5	0.3	3	11.8	1.8	6
L5	1.2	0.3	3	0.2	0.1	2	14.7	1.2	3

for near-continuous air quality determinations. The device aspirates air at a rate of 16.7 L min^{-1} and collects the suspended particulates with in-line cyclones designed for 50% cut efficiency of either 10- or 2.5-μm particles. Aerosols passing the cyclones are collected on a glass fiber filter housed in an environmentally controlled chamber to limit the influence of water vapor on the measurement of filter mass. The data storage parameters in the TEOM were set to collect average filter mass measurements every minute for the duration of experimental runs. Separate tests were conducted with PM$_{10}$ and PM$_{2.5}$ cyclones.

The self-abrader emitter (Fig. 1) consisted of a stainless steel cone 530 mm high with a bottom diameter of 57 mm and a top diameter of 205 mm. It was attached to a pressurized air source with a desiccant filter and an in-line flow rate controller and monitor. The pressurized air (0.1 MPa) entered the soil abrader at 5.5 L min^{-1} through a 1-mm tube mounted tangentially to the inner opening of the inlet collar (Fig. 1b, and 2a,b) at the base of the cone. A solid removable end piece with an indented soil cup (Fig. 2c) was bolted under the air inlet collar to close the lower end of the abrader cone and placed the soil sample in line with the tangential incoming air stream. A circular steel cover plate was bolted to the top of the cone. The (12.5-mm) inlet tube to the TEOM was inserted 100 mm through an opening in the center of the cover plate to aspirate air from the abrader cone and continually monitor PM$_{10}$ or PM$_{2.5}$ emissions. The inlet flow differential between the TEOM (16.7 L min^{-1}) and the abrader cone (5.5 L min^{-1}) ensured that no dust was forced outside of the abrader cone. A continuously rotating tapping mechanism (Fig. 1), vibrated the cone to release any soil clinging to the smooth interior walls by striking the cone on the cover. This was constructed of a spring-loaded tapping arm connected to a rotating steel ring and driven by an electrical motor at 100 rpm throughout each experiment.

To document the emitter cone performance, the air velocity was measured along the interior wall of the abrader with a hot-wire velocity probe (Model 8500D-II; Alnor Instrument Co., Skokie, IL). A power relationship was found between the air velocity 5 mm from the cone wall and the height in the cone from 0.20 to 0.45 m above the air inlet:

$$u_{5mm} = 0.481h^{-1.1} \qquad r^2 = 0.96 \qquad [1]$$

where u_{5mm} is the measured velocity (m s^{-1}) at a distance of 5 mm from the cone wall and h is the height (m) from the bottom of the cone. The reduced velocity with height caused the soil sample to be totally entrained at the cone base and differentially suspended along the cone side at varying heights depending on the particle or aggregate diameter. No soil reached the cone top except that fully suspended and aspirated by the TEOM.

At the start of an experiment, an air-dry preweighed sample of soil (~0.25–0.50 g) was placed in the soil cup and attached to the cone bottom. The air stream was initiated in the cone to entrain the soil from the bottom end-piece and propel it tangentially in a rotating motion upward within the cone. The suspended particles formed an active abrasion zone where they tumbled and slid along an elliptical path on the cone's interior surface ~0.15 to 0.35 m above the base of the cone. At the test start, the soil in the cup was gently stirred with a long wire inserted through the top-plate opening to insure complete entrainment by the air stream. The tapping caused the release of smaller aggregates deposited on the cone wall to fall downward for additional abrasion action. Each soil sample was tested for 1 h. The PM$_{10}$ or PM$_{2.5}$ emission potential of the sample, expressed as the mass percentage of the original soil sample, was determined from the accumulated TEOM mass over the run period. The cone was disassembled and cleaned with compressed air between samples.

The self-abrader method was used to evaluate soil samples collected from 44 sites on the Columbia Plateau in eastern Washington and from four sites in western Texas. The soils from Washington were formed from eolian dunes and loess, have a texture range from sandy loams to silt loams and all are poorly aggregated, with <1.2% organic C (Marks, 1996). The soils, shown in Fig. 3, are classified as Xeric Torripsamments (Dq), Xeric Haplocambids (Ds and L1), Calcidic Haploxerolls (L2), Typic Haploxerolls (L3), and Pachic Haploxerolls (L4 and L5) (Soil Survey Staff, 1998). Samples of each soil were air dried, passed through a 2-mm sieve to remove larger residue and aggregates, and were subsampled by a mechanical splitter to obtain five test samples for each experiment.

Dispersed particle-size distributions for all soils were measured by laser diffraction (Malvern Instrument, Malvern, En-
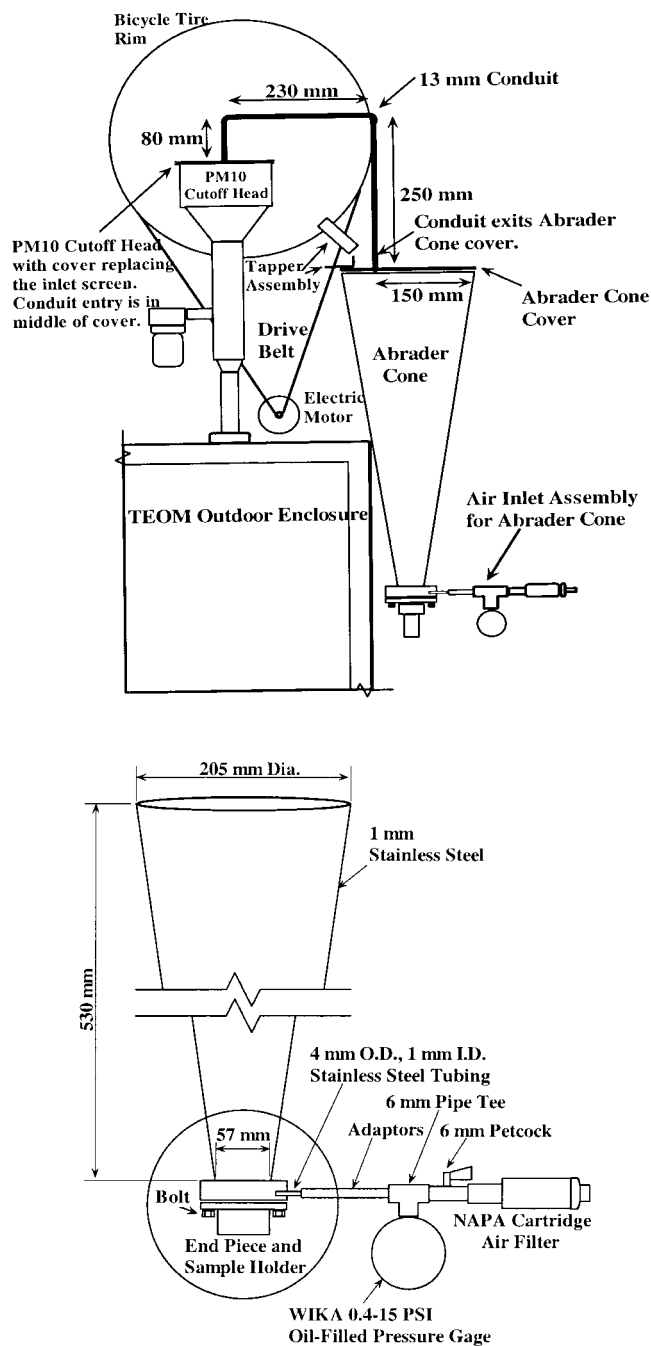
Fig. 1. Abrader cone mounting and dimension detail.

gland). The instrument employed a 2-mW HeNe 633-nm laser and calculated equivalent spherical particle diameter from Mie scattering theory for 65 size increments smaller than 800 μm. Sample pretreatment consisted of removing carbonates by boiling with sodium acetate, oxidizing organic matter by boiling with hydrogen peroxide and removing dissolved materials by centrifugation and decantation. The primary samples were dispersed with sodium hexametaphosphate by agitation for 16 h prior to analysis. Following dispersion but prior to measurement, coarse sands were removed by wet sieving with a 1000-μm wire-mesh screen. Laser diffraction is a volumetric measurement of particles, whereas the TEOM is a gravimetric measurement. Assuming a constant particle density for these mineral soils, the measurement units (by percent) are nearly equivalent.

Calibration

To calibrate the self-abrader emitter apparatus, Fine Arizona Road Dust (ARD, Powder Technology Inc., Burnsville MN) was combined in six proportions with silica sand. The ARD is a commercially available standardized particulate material generally specified as having 50% particulates less then PM_{10}. The silica sand was commercial sandblasting sand that was first washed and air-dried to remove any dust. Test samples were formulated that weighed ~0.25 g and ranged in composition from pure sand (0:1) to pure ARD (1:0). Clean sand emitted negligible PM_{10} (Fig. 4). When ARD was included in the proportion of 1:9 ARD/sand, PM_{10} release was relatively steady after a small initial pulse. Proportionately larger initial PM_{10} pulses (Fig. 4) accompanied further increases in the ratio of ARD to sand. Following the initial pulse, all samples continued to release PM_{10} at relatively steady, albeit different, rates, evidently as a result of continued abrasion of the ARD by the sand.

Two analytic methods were used to determine the PM_{10} mass emitted. The first approach estimated only the quantity of PM_{10} released in the initial pulse by a graphical technique. This consisted of finding the PM_{10} value at the intersection of lines tangent, respectively, to the accumulative concentration record for the period during the initial PM_{10} release pulse and the period of slow PM_{10} release thereafter (Fig. 4). The second approach considered the total PM_{10} mass emitted after 1 h of testing. Comparison of the results from the two approaches showed that the initial pulse comprised ~90% of the 1-h PM_{10} for the ARD/sand mixtures and 66% of the 1-h PM_{10} for the tested soils (Fig. 5). Since the 1-h cumulative PM_{10} value was more objective and applicable to soils of widely varying aggregate stability, it was used for all subsequent comparisons. A linear response over the wide range of PM_{10} contents of the ARD/sand mixtures with the 1-h PM_{10} emission values confirmed the analytic method and the system calibration (Fig. 6).

To develop a predictive relationship for PM content of other soils not sampled but included in traditional textural data sets, volumetric PM_{10} and $PM_{2.5}$ content determined by laser diffraction analysis of dispersed soil samples were compared with PM_{10} and $PM_{2.5}$ values obtained from the self-abrader (Table 1). A strong linear correlation between dispersed and self-abrader PM_{10} mean values for each soil mapping unit was obtained (Fig. 7). A similar relationship for $PM_{2.5}$ was not apparent.

RESULTS AND DISCUSSION

The calibration tests with ARD confirmed the difference between dispersed and nondispersed analyses. The particle-size distribution for dispersed samples of fine ARD from a Malvern Mastersizer, and from a Coulter Multisizer AccuComp that was provided with the sample, documented that the ARD was >50% PM_{10}. The nondispersed self-abrader data showed that the ARD contains ~14% readily emittable PM_{10} (Fig. 6), or only ~30% of that measured by the dispersed techniques. This result underscores the importance of the use of techniques that do not disperse soil samples in wind erosion and dust emission appraisal (Shao et al., 1996).

Gravimetric PM_{10} and $PM_{2.5}$ emission potentials, by both resuspension and self-abrasion techniques, are presented in Table 1 as averages for selected mapping units of the Washington state general soil map (Fig. 3, Boling et al., 1998) and the Texas soils. The PM_{10} and $PM_{2.5}$

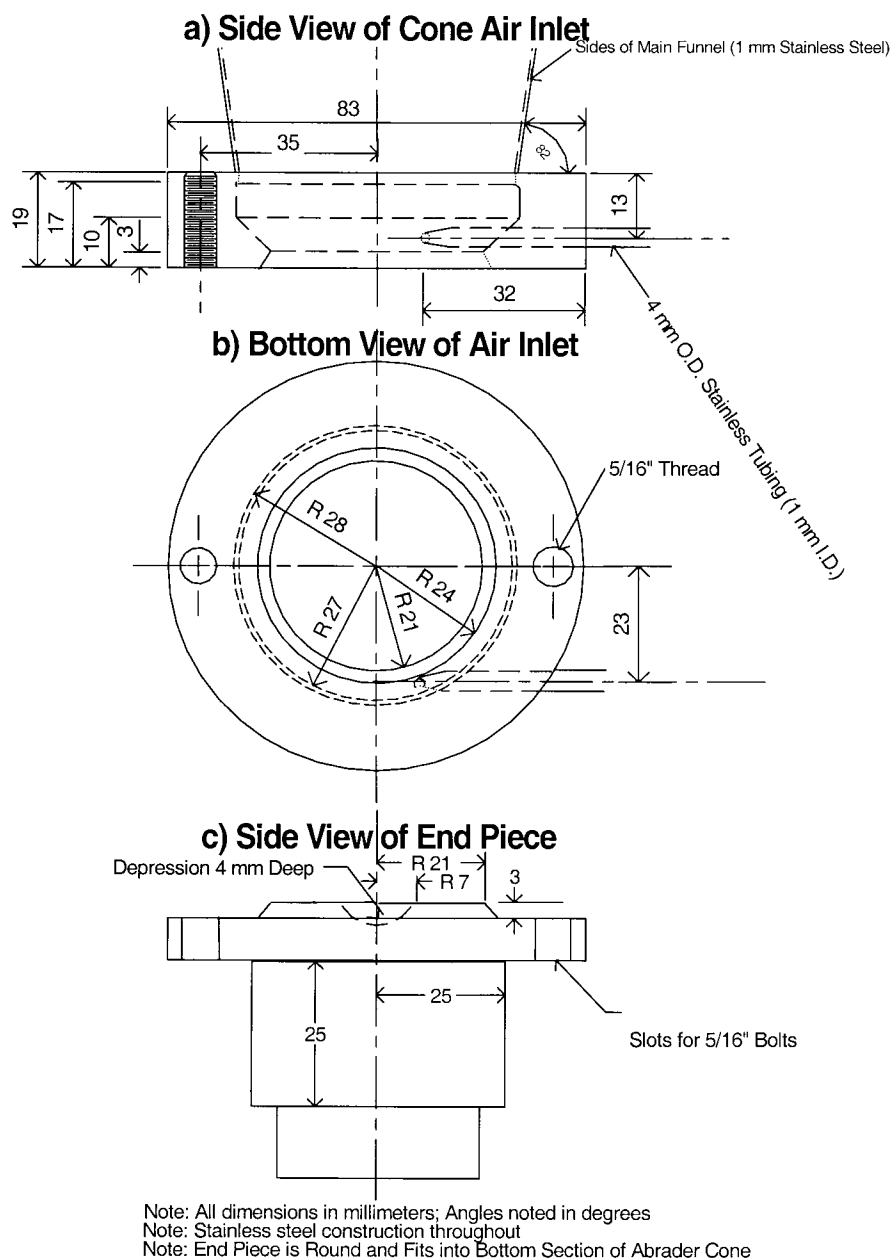**a) Side View of Cone Air Inlet**

Sides of Main Funnel (1 mm Stainless Steel)

4 mm O.D. Stainless Tubing (1 mm I.D.)

b) Bottom View of Air Inlet

5/16" Thread

R 28
R 24
R 27
R 21
23

c) Side View of End Piece

Depression 4 mm Deep — R 21 — R 7   3

25
25

Slots for 5/16" Bolts

Note: All dimensions in millimeters; Angles noted in degrees
Note: Stainless steel construction throughout
Note: End Piece is Round and Fits into Bottom Section of Abrader Cone

Fig. 2. Details of soil abrader inlet collar and cone end.

values obtained from the self-abrader experiments are three to six times greater than those previously determined by the resuspension technique. This will significantly increase the computed dust fluxes in the dust emission model developed by Saxton et al. (2000) and will reduce the magnitude of the empirical dust correction coefficient applied in a regional air quality model (Lee, 1998). The $PM_{2.5}$ emission potentials of soils obtained from the self-abrader were 30 to 55% of the PM_{10} potentials. Therefore, dust emissions from wind erosion in this region will impact air quality, regardless of whether standards are based on PM_{10} or $PM_{2.5}$ concentrations.

The relationship between self abrader emissions and dispersed PM_{10} content of the Washington soils (Fig. 7) generally followed a spatial pattern based on their geography, origin, and properties. Soils of the Dq, Ds, L1, L2, L3, L4, and L5 map units comprise a sequence of eolian soils in the regional windshed and climatic gradient (Fig. 3, Boling et al., 1998), from sandy dunes near the sediment source (Dq) to increasingly source finer textures in the down-wind distance (Ds-L5). Systematic increases in rainfall, water holding capacity, and clay content of these soils is reflected in increasing organic matter content and aggregate formation (Marks, 1996). Soils in the Dq map unit are very sandy and are often formed on dunes in the driest part of the Columbia Plateau, where rainfall averages <~250 mm per year. They had little stabilizing native vegetation and have been continually worked by wind throughout the Holocene Epoch so that today they continue to be very erodible by wind, but they contain little PM_{10} by either dis-
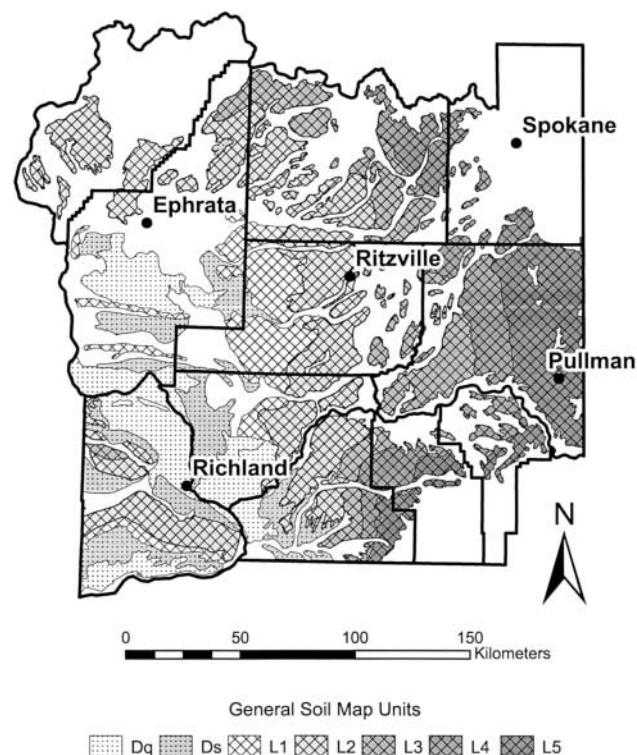
Fig. 3. Soils of the Columbia Plateau, from General Soil Map of Washington (Boling et al., 1998).
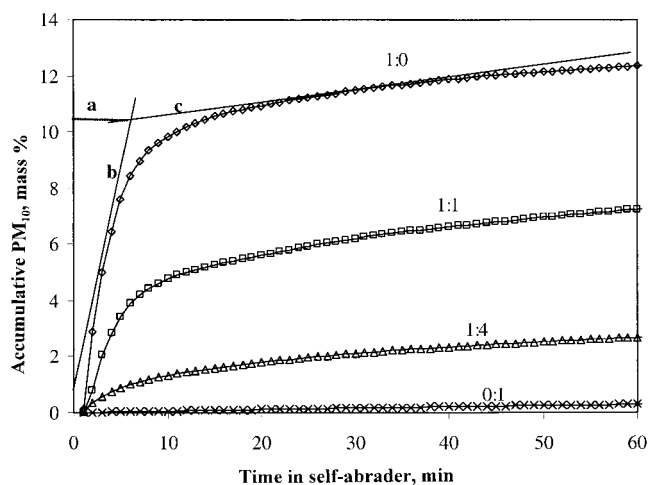

Fig. 4. Accumulative PM_{10}, expressed as mass percentage of the total sample for mixtures of fine Arizona Road Dust and sand. The accumulative PM_{10} value at the intersection of tangents (a) to the accumulative PM_{10} record during the initial release (b) and abrasion (c) periods was used to estimate the PM_{10} emitted during the initial release.

persed analysis or self abrader experiments. Soils of the L1 and Ds map units have higher amounts of both dispersed and self-abrader PM_{10} than those of the Dq unit. The self-abrader PM_{10} emission values from these soils are quite similar because of their proximity and similarity of surface horizons. Soils in map units L2 to L5 continue the progression to finer textures (~5, 20, 75 to 15, 75, 10% clay, silt, and sand, respectively) and increased organic matter content (~0.2 to 1.2%) into the more distal parts of the eolian system of the plateau.
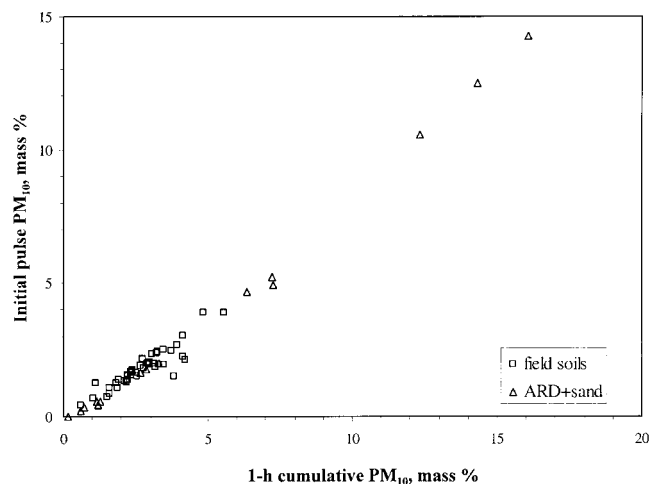

Fig. 5. The particles <10 μm (PM_{10}) values for soil samples and mixtures of sand and fine Arizona Road Dust, as determined for the one hour test and for the initial pulse of PM_{10}.
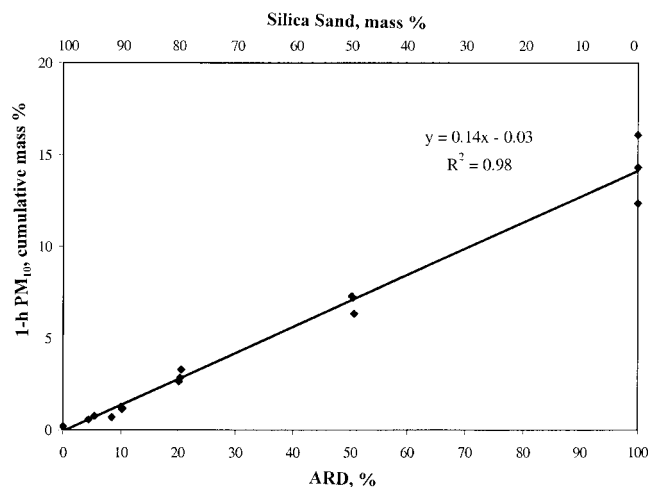

Fig. 6. The particles <10 μm (PM_{10}) generated from mixtures of sand and fine Arizona Road Dust during 1 h tests by the self-abrader.

Fining of these eolian soils with position in the regional windshed is reflected in the stepwise increase in PM_{10} content of dispersed samples and the proportional increase in self-abrader PM_{10} emission values (Fig. 7).

It would be expected that along a downwind transect, the potential for PM_{10} release would first increase, because of fining of the soil texture, and decrease, because of greater aggregate stability with increasing organic content. The results (Fig. 7) however, showed a continuing increase. The most apparent reason for this discrepancy is aggregate destruction by the farming system, since all of the experimental soils from Washington were collected from farm fields that had been in a dust mulch summer fallow rotation for many years, causing substantial loss of aggregates from the tillage zones.

CONCLUSIONS

A laboratory technique to determine PM_{10} and $PM_{2.5}$ potential emissions, which accounts for the effects of aggregate stability and particle size, was developed, calibrated, and tested. Calibration with mixtures of ARD
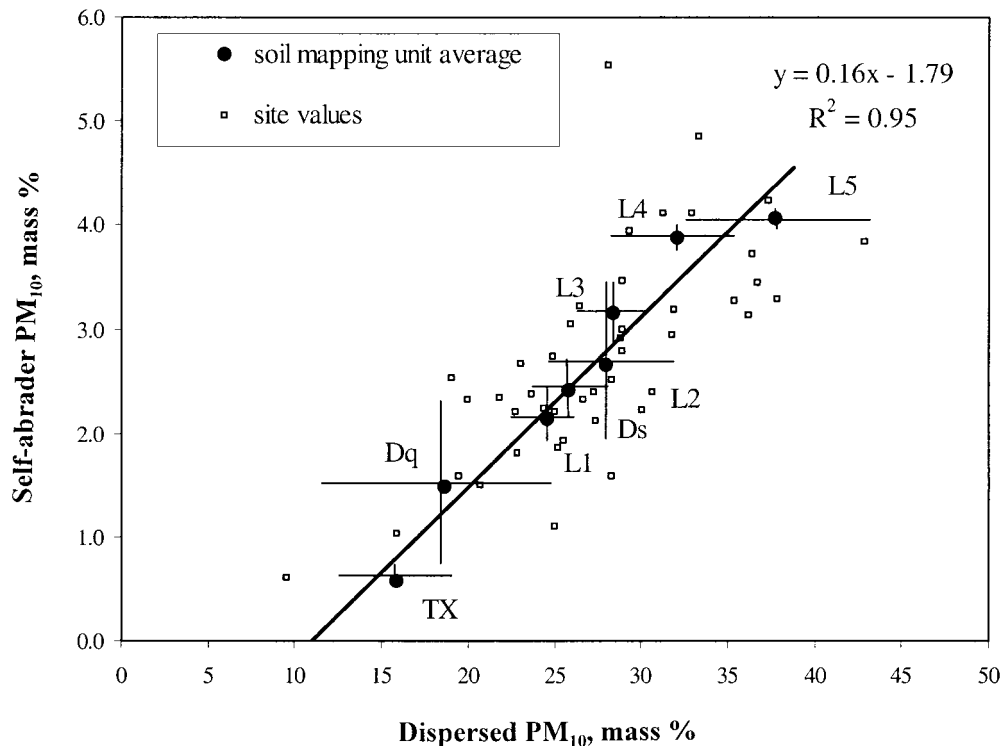
Fig. 7. The particles <10 μm (PM_{10}) emission potentials obtained from the self-abrader versus those from dispersed analysis for each tested soil and the average values and 95% confidence intervals for the values aggregated by general soil mapping unit.

and clean sand provided a linear result, but also clearly documented the difference between results from methods in which the soils have been dispersed and those in which they have not. Whereas $>50\%$ of the particles in dispersed ARD are <10 μm, the nondispersed self-abrader analyses showed the PM_{10} emission potential was only ~14%. The self-abrader technique is accurate and reproducible for eolian soils of the Columbia Plateau and selected Texas soils within the sampling and management variability. Results generally agreed with expected spatial patterns across the study region. A correlation was established for PM_{10} between dispersed particle sizing and the self-abrader nondispersed values to provide broader applications with the widely available traditional soil analyses.

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